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May 31, 2005

International Journal of Impact Engineering

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Simulation of Hypervelocity Penetration in Limestone

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Abstract

A parameter study was performed to examine the (shock) damage obtained with long-rod and spherical mono-material penetrators impacting two varieties of limestone. In all cases, the impacts were assumed to be normal to the plane of the rock and at zero angle of attack (in the case of the rods). Impact velocities ranged to 15 km/s but most calculations were performed at 4 and 6 km/s and the penetrator mass was fixed at 1000 kg. For unlined underground structures, incipient damage was defined to occur when the peak stress, σ_{pk} , exceeds 1 kb (100 MPa) and the applied impulse per unit area, I_{pk} , exceeds 1 ktap (1 kb- μ s). Severe damage was assumed to occur when σ_{pk} exceeds 1 kb and I_{pk} exceeds 1000 ktaps. Using the latter definition it was found that severe damage in hard, non-porous limestone with spherical impactors extended to a depth of 9 m on-axis for an impact velocity of 4 km/s and 12 m at 6 km/s. Cylinders with length-to-diameter (L/D) ratio of 8.75 achieved depth to severe damage of 23 m and 40 m, respectively under the same conditions. For a limestone medium with 2% initial gas porosity, the latter numbers were reduced to 12 m and 18 m.

Keywords: Penetration, Impact, Simulation, Damage, GEODYN.

1. Introduction

Hard and Deeply Buried Targets (HDBT) present a significant challenge to military planners. Likewise, the survival of valuable assets, and the protection of these assets from potential hostile attack, is equally challenging. Conventional weapons are often incapable of defeating HDBTs. In this paper, we consider an alternative approach that relies on the kinetic energy from hypervelocity impacts to achieve target defeat.

Hypervelocity penetrators are potentially one such method. Conventional reentry vehicles are able to attain terminal velocities in the 4-6 km/s range and rocket assisted schemes might produce even higher values. At 4 km/s the specific energy obtained via direct impact is twice that available from conventional explosives and at 6 km/s the gain factor increases to 4.5. Moreover, this energy is delivered in a more efficient manner to produce ground shock. And finally, reentry vehicles are capable of reaching virtually any point on the Earth within roughly 30 minutes so that the time delay to attack a given target will typically be much less than with conventional air-delivered ordnance.

A question arises as to the effectiveness of this so-called "Rods-from-God" [1] approach, i.e.,

exactly how much damage can be expected? The purpose of this report is to attempt to provide at least a preliminary answer to this question. We have conducted a brief parameter study to examine the (shock) damage obtained with long-rod and spherical penetrators of various (mono) materials impacting on two types of limestone.

2. Approach

The parameter study was carried out using GEODYN [2,3], a multidimensional, Godunov based Eulerian hydrocode with adaptive mesh refinement capability. Among its many features, the code includes a high-order interface reconstruction algorithm and a unique remapping capability that allows the overlay of sub-domains onto an existing grid at any point during a simulation.

Four different projectile materials were evaluated: iron, tungsten, aluminum, and stainless steel. Two different limestones were considered, both of which had been previously investigated for shock propagation purposes. Linchburg limestone is a hard, non-porous material in which a lead mine had been constructed near the town of Magdalena, New Mexico. A constitutive model for this limestone was formulated when decoupling explosion experiments were conducted in this abandoned mine in 1996 [4]. The model for St.-Genevieve limestone was formulated to predict tunnel collapse experiments that were conducted in an active quarry in Indiana in 2005 [5]; this material has a gas porosity of 2.7%.

Calculations were made with two different projectile geometries, spheres, and long rods with length-to-diameter (L/D) ratio of 8.75. In all cases, the mass of the projectile was fixed at 1000 kg and the impacts were assumed to be normal to the rock interface, with zero angle of attack in the case of the rods. This allowed axial symmetry to be employed. The minimum zone size employed was 12.5 mm, which assured that at least 16 zones spanned the diameter of the impacting tungsten cylinders; all other materials and geometries had concomitantly more zones across the impact cross-section.

3. Computational Strategy

The GEODYN code used in this study employs adaptive mesh refinement thus making it possible to focus computational resources where resolution is needed to better define material interfaces and shock fronts. The adaptively refined regions evolve in space and time with the possibility of new regions being created and existing regions being deleted as required by the rapidly evolving dynamic environment of the simulation. The adaptive mesh refinement methodology used in GEODYN also allows for coarsening of the entire computational domain, making it possible to simulate more efficiently late time phenomena occurring long after the passage of the shock front and having lower resolution requirements.

The same computational strategy was used in all the simulations performed during the course of this study. The baseline cell size of the entire computational domain was 100 mm. Two levels of refinement were introduced. The first reduced the linear dimension of the cells by a factor of four and the second reduced it by another factor of two, leading to a minimum cell size of 12.5 mm. Problem size ranged between about one million zones (corresponding to low velocity impact) and a little over ten million zones (corresponding to high velocity impact).

4. Numerical Convergence

A mesh sensitivity study was performed to assess convergence of the numerical solution. In addition to the 12.5 mm resolution used in the main simulations as described above, the sensitivity study included two other coarser resolutions of 25 mm and 50 mm. The adaptive mesh refinement strategy was kept the same as previously described.

The results presented in this section correspond to the impact of a 1000 kg steel sphere into a St. Genevieve limestone half space. Simulations of impact into Lynchburg limestone had similar convergence characteristics.

Fig. 1 shows pressure and velocity histories at distances of 3 m and 5 m directly below the spherical penetrator. The results are very similar, with the simulation employing 50 mm cells resulting in a decreased peak magnitude, and slight spreading of the shock front. Similar observations apply to waveforms throughout the computational domain, including the off-axis waveforms shown in Fig. 2.

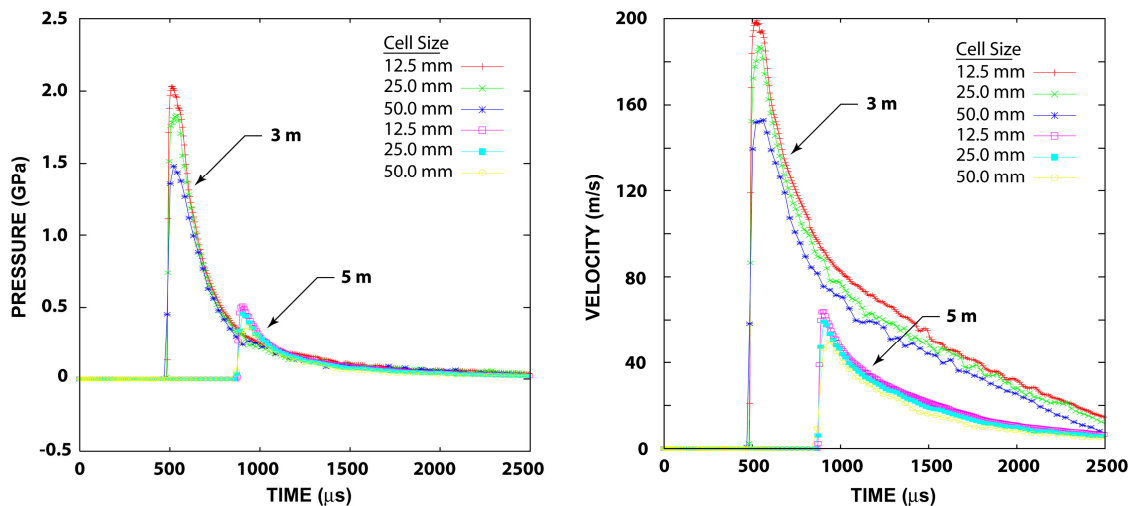


Fig. 1. Simulated pressure and particle velocity histories directly below a spherical steel penetrator from three simulations with cell sizes of 12.5 mm, 25 mm, and 50 mm.

Craters from the simulations performed at resolutions of 25 mm and 12.5 mm are shown in Fig. 3. The craters dimensions from the two simulations are virtually identical. Minor differences in the ejecta field occur because the smallest dimension of the jetting material is on the order of the cell size. These differences do not affect the response of the geologic medium to the shock waves emanating from the impact site. Minor differences are also observed in the localization patterns in the material immediately surrounding the crater. These are associated with dilatancy and damage, and they are not believed to have a significant effect on the response of the medium away from the impact site.

The results of this sensitivity study demonstrate that the adaptive mesh refinement strategy used in the simulations leads to converged solutions for cell sizes below about 25 mm. A cell size of 12.5 mm was used throughout the remainder of this study.

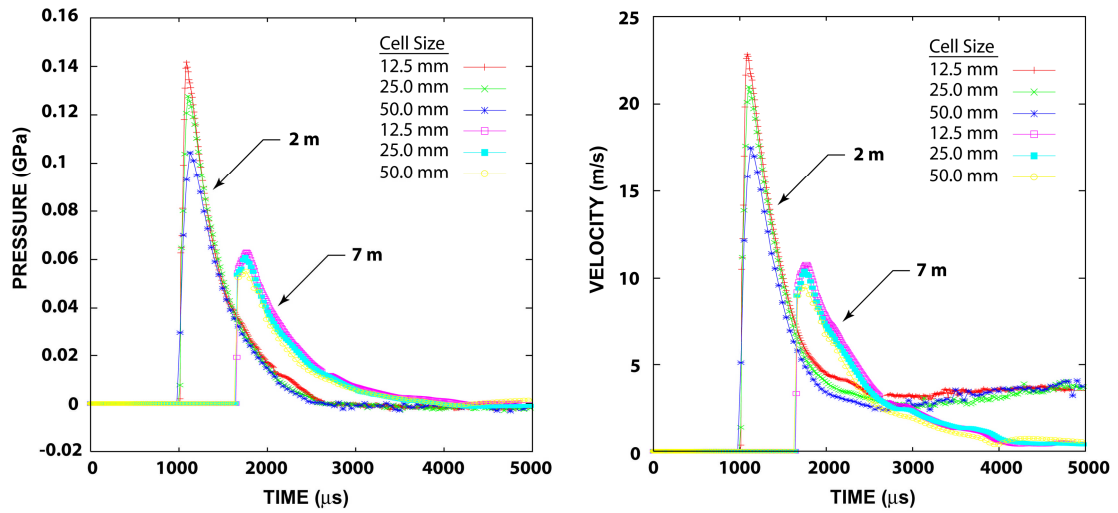


Fig. 2. Simulated pressure and particle velocity histories from three simulations with cell sizes of 12.5 mm, 25 mm, and 50 mm. The results shown are for two off-axis locations, 2 m and 7 m below the impact plane and a horizontal offset of 5 m.

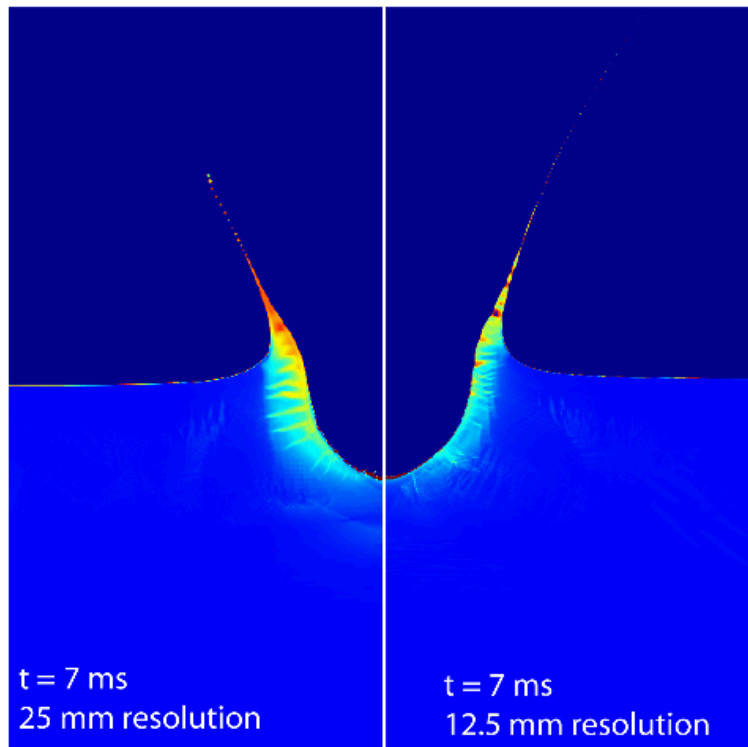


Fig. 3. Craters from two simulations with cell sizes of 12.5 mm and 25 mm.

5. Effect of Projectile Velocity on Depth- and Range-to-Effect

It is well known that the depth of penetration for hypervelocity impact is proportional to the length of the penetrator and to the square root of the ratio of penetrator to target density. Moreover, above a given velocity, typically 3-5 km/s, the depth of penetration is roughly independent of projectile velocity. Our calculations confirmed these results; in no case did the depth of penetration exceed 5 m and in most cases, it was considerably less. This, of course, was no surprise as we assumed from the beginning that the range and depth for shock damage would greatly exceed the depth of the crater. Past studies have shown that unlined underground structures typically suffer significant damage when the peak stress applied exceeds 1 kbar (100 MPa) [6]. Accordingly, Figs. 4 and 5 depict the depth-on-axis and the maximum range to 1 kb peak stress as a function of projectile velocity for both spherical and long-rod cylindrical impactors on the Linchburg (non-porous) limestone. Fig. 6 shows snapshots of peak stress produced by the impact of a steel sphere into St. Genevieve limestone at velocities of 2, 3 and 5 km/s.

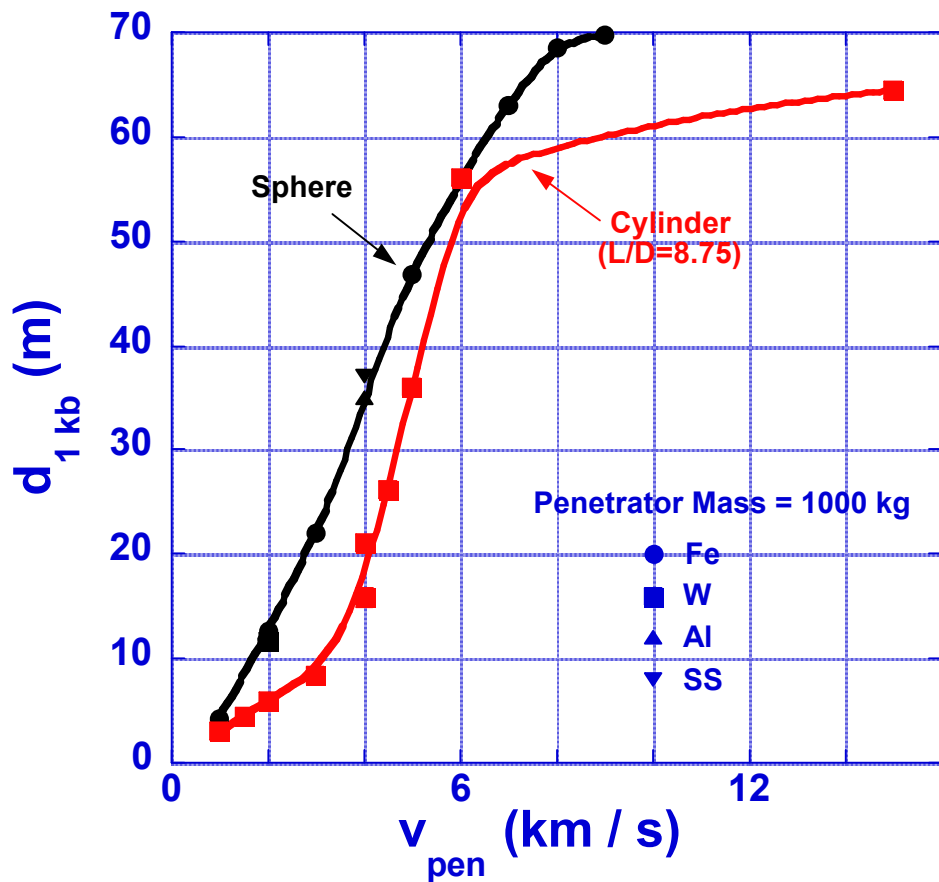


Fig. 4. Depth-on-axis to 1 kb peak stress as a function of initial projectile velocity for spherical and long-rod cylindrical impactors. Projectile materials were iron, tungsten, aluminum and stainless steel. The projectile mass in all cases was 1000 kg. Target material was Linchburg (non-porous) limestone.

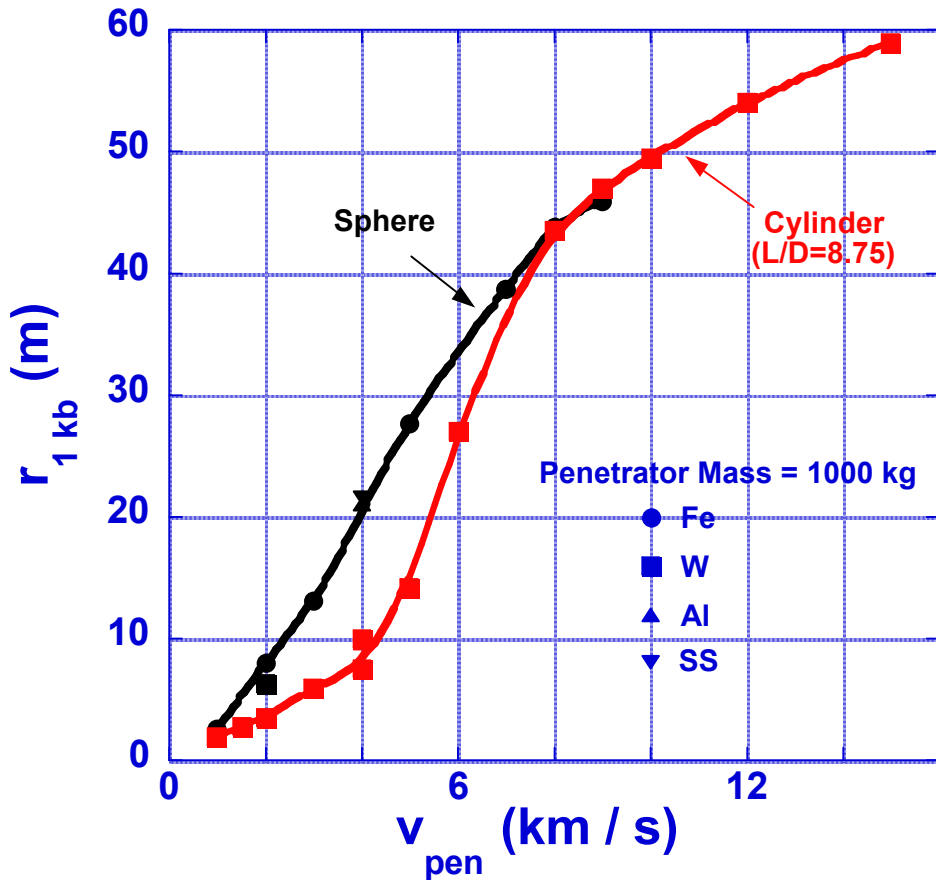


Fig. 5. Maximum range to peak stress of 1 kb as a function of initial projectile velocity for spherical and long-rod cylindrical impactors. Projectile materials were iron, tungsten, aluminum and stainless steel. The projectile mass in all cases was 1000 kg. Target material was Linchburg (non-porous) limestone.

A number of points are immediately apparent. First, the depth- and range-to-peak stress appear independent of projectile material, in contrast to penetration depth, which varies roughly with the square root of the projectile density, as mentioned earlier. Second, both depth- and range-to peak stress are significantly higher for the sphere than for the long-rod, which is 5.6 times longer (and penetrates much further into the rock). Although the spherical penetrators appear to produce greater effects than long rods of the same mass, further examination shows that the long-rods produce much larger peak displacements (due to pulse shape). Fig. 7 exemplifies this for the case where the penetrator velocity is 4 km/s.

Fig. 7 also suggests why the 1 kb peak stress criterion, while useful as a nuclear explosion damage criterion, may not be entirely adequate for describing damage resulting from hypervelocity impact. At this stress level, the peak displacement on axis for the spherical impactor is only 1.2 mm and for the cylinder 3.4 mm. Such small displacements may produce some spall but are unlikely to cause any significant structural damage. Clearly, an additional criterion is required. Here we introduce the notion

of applied impulse per unit area (the integral of stress over time at a given Eulerian location). For unlined underground structures we define incipient damage as occurring when the peak stress, σ_{pk} , exceeds 1 kb and the applied impulse per unit area, I_{pk} , exceeds 1 ktap (1 ktap = 1 kb- μ s). Since the wave speed in most rocks is ~ 4 -6 mm/ μ s, a 1 kb pulse at 1 ktap will engage at most 4-6 mm of rock, and minor spall may result. Conversely, we define severe damage as occurring when σ_{pk} exceeds 1 kb and I_{pk} exceeds 1000 ktaps. In this case, the extent of the rock mass engaged is 4-6 m, typical of the size of many underground openings. Also, if σ_{pk} significantly exceeds 1 kb, severe damage may occur at lower values of I_{pk} , say 200 ktaps.

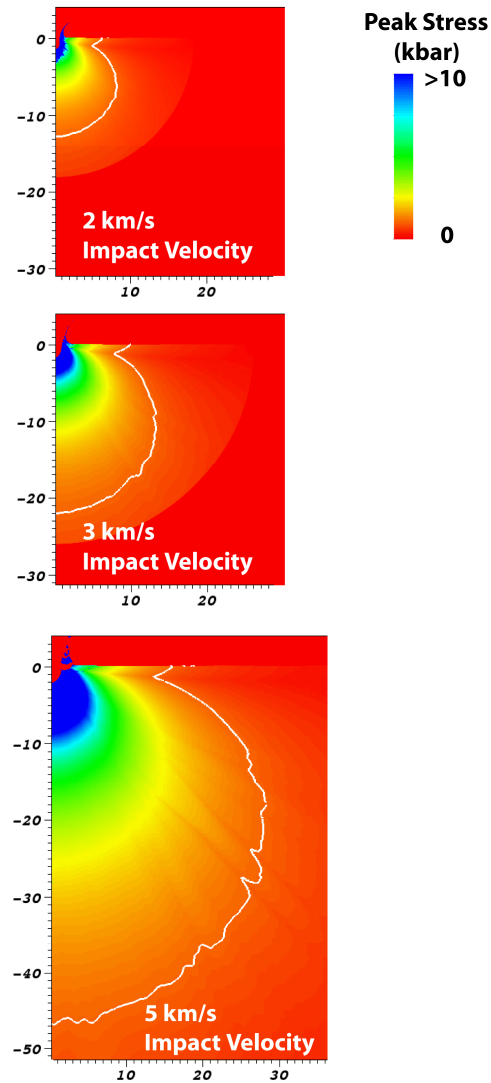


Fig. 6. Snapshots of peak stress produced by the impact of a 1000 kg steel sphere into St. Genevieve limestone at velocities of 2, 3 and 5 km/s. The contours shown correspond to a peak stress level of 1 kbar. Dimensions are in meters.

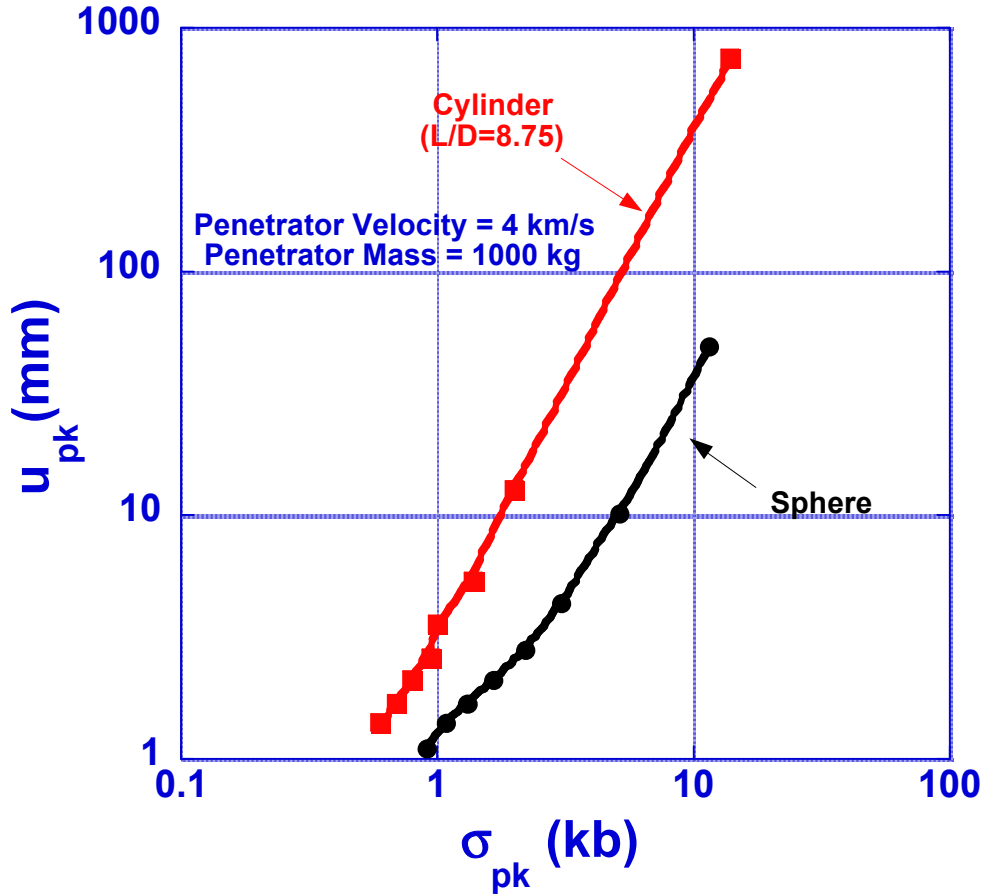


Fig. 7. Peak on-axis displacement as a function of peak stress for the case where the penetrator velocity is 4 km/s.

6. Damage at Impact Velocity of 4 km/s

Fig. 8 shows both the peak stress and applied impulse per unit area as a function of depth-on-axis for spherical and long-rod penetrators into both porous and nonporous limestone.

For the non-porous limestone, the on-axis depth to 1 kb peak stress is seen to be approximately 23 m for the long-rod, with a concomitant value of I_{pk} of 840 ktaps. For the spherical impactor the on-axis depth to 1 kb is roughly 35 m, but at this depth I_{pk} is only 11 ktaps. At 23 m, σ_{pk} for the spherical impactor is 1.7 kb and I_{pk} is 30 ktaps. The result is that a long-rod impactor would produce nearly severe damage to a depth of 23 m whereas a spherical impactor of the same mass would yield only light damage (28 times less peak impulse) at this depth. Severe damage may be obtained with a spherical impactor at a depth-on-axis of 9 m ($\sigma_{pk} = 5.8$ kb and $I_{pk} = 220$ ktaps).

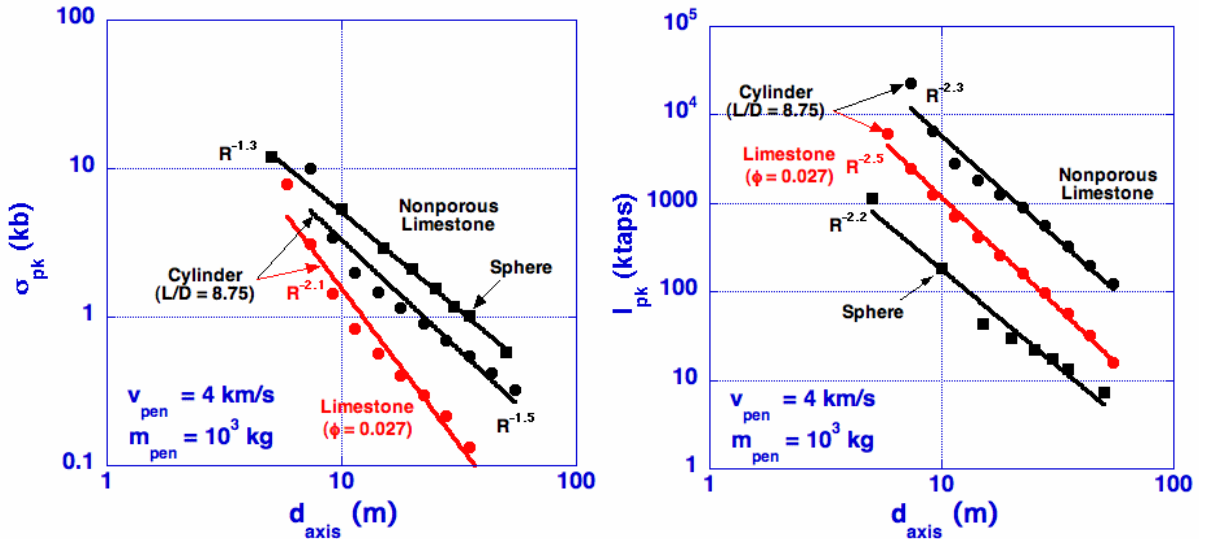


Fig. 8. Peak stress and applied impulse per unit area as a function of depth-on-axis for spherical and long-rod cylindrical penetrators into both porous and non-porous limestone for an initial impact velocity of 4 km/s.

When porosity is introduced, however, the depth-to-effect is seen to decrease significantly. Again, for the long-rod, the depth to 1 kb peak stress drops from 23 m for the Linchburg limestone to 12 m for the St. Genevieve (2.7% gas porosity). The applied impulse per unit area decreases from 840 to 760 ktaps. This shows that the peak impulse per unit area, for fixed peak stress, is relatively independent of rock type and the depth-to-effect is halved in the porous medium because of the attendant energy dissipation.

7. Damage at Impact Velocity of 6 km/s

Fig. 9 shows the peak stress and applied impulse per unit area for the 6 km/s case. For this initial projectile velocity, and for the nonporous limestone, the peak stress on-axis is observed to not be significantly affected by penetrator shape. The impulse per unit area for the long-rod is approximately the same as obtained at 4 km/s but the peak stress at the same depth is approximately 4 times greater. At a depth of 40 m, $\sigma_{pk} = 1.7$ kb and $I_{pk} = 200$ ktaps so that severe damage for this configuration may extend to this depth.

The spherical impactor is still comparatively ineffective at the same depth on axis as the long rod because I_p for the latter is an order of magnitude greater. Attenuation rates appear to be similar to those observed at 4 km/s for both geometries.

I_p for the long-rod in the Linchburg (non-porous) limestone, as a function of depth-on-axis, is roughly the same as attained at 4 km/s, but for the St. Genevieve (2.7% gas porosity) it is roughly

double. Severe damage for the Linchburg may extend to 40 m depth on axis ($\sigma_{pk} = 1.7$ kb and $I_{pk} = 200$ ktaps) and possibly to 18 m for the St. Genevieve ($\sigma_{pk} = 1.0$ kb and $I_{pk} = 475$ ktaps).

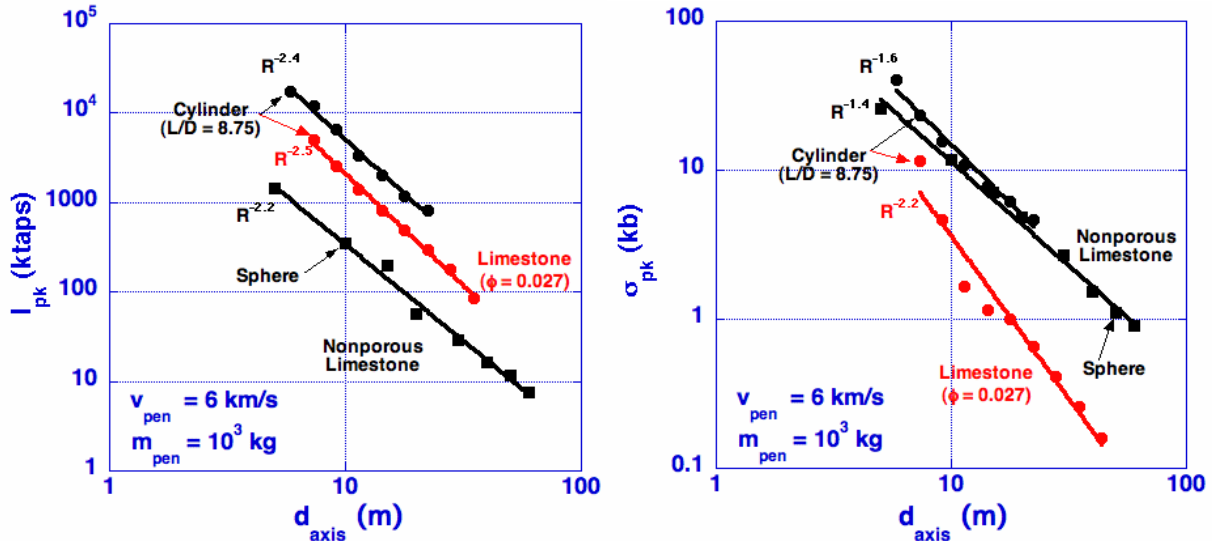


Fig. 9. Peak stress and applied impulse per unit area as a function of depth-on-axis for spherical and long-rod cylindrical penetrators into both porous and non-porous limestone for an initial impact velocity of 4 km/s.

8. Summary and Conclusions

We conducted a brief study of the damage that might be expected from hypervelocity projectiles impacting on limestone targets. It was found that said damage is independent of projectile material (for the same mass projectile). Although the crater depth is relatively independent of the projectile velocity, the depth to severe damage by shock loading is strongly affected thereby, nearly doubling when the initial velocity is increased from 4 to 6 km/s against nonporous limestone targets. The effect of 2.7% gas porosity in the rock is also dramatic, reducing the depth to severe damage by roughly half as compared with nonporous limestone. For long-rod cylindrical projectiles with $L/D=8.75$ and mass of 1000 kg, severe damage to underground structure may be achieved at depths to 12 m in the porous rock at 4 km/s and to 40 m in the non-porous rock at 6 km/s.

Acknowledgements

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory (LLNL) under contract No. W-7405-Eng-48.

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